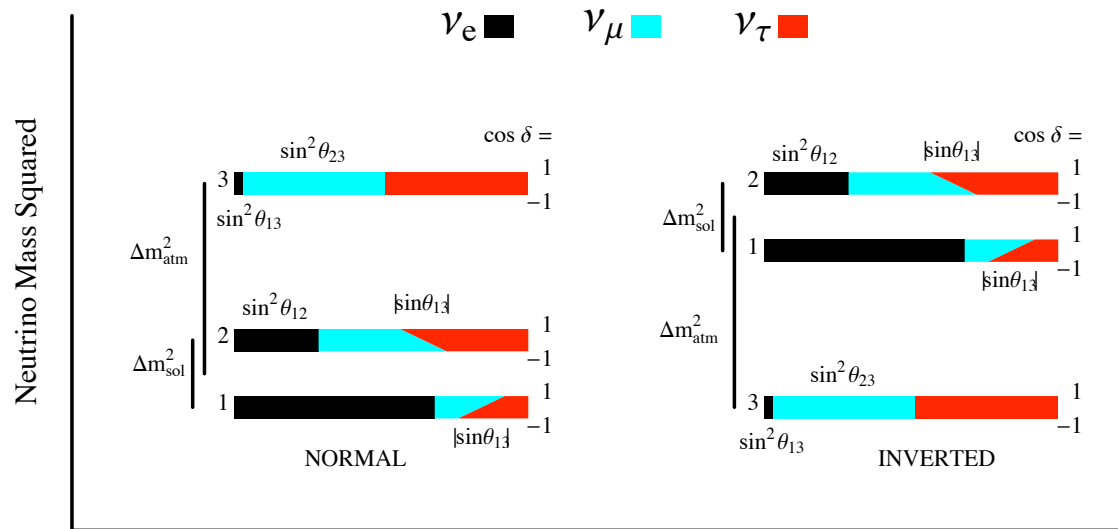# θ_{13}

Stephen Parke
Fermilab:

- ν_e fraction of ν_3: $- \sin^2 \theta_{13}$

- mass hierarchy: $- \operatorname{sign} \text{ of } \delta m_{31}^2$

- CP violation: $- \sin \delta \neq 0$
observable

ν_e ■ ν_μ ■ ν_τ ■

Neutrino Mass Squared

$\sin^2\theta_{23}$ $\qquad\qquad$ $\cos\delta =$
3 $\qquad\qquad\qquad\qquad$ 1
$\sin^2\theta_{13}$ $\qquad\qquad\qquad$ −1

Δm^2_{atm}

Δm^2_{sol}

$\sin^2\theta_{12}$ $\qquad$ $|\sin\theta_{13}|$
2 $\qquad\qquad\qquad\qquad$ 1
$\qquad\qquad\qquad\qquad$ −1
1 $\qquad\qquad\qquad\qquad$ 1
$\qquad\qquad\qquad$ −1
$|\sin\theta_{13}|$

NORMAL

$\sin^2\theta_{12}$ $\quad$ $|\sin\theta_{13}|$ $\quad$ $\cos\delta =$
2 $\qquad\qquad\qquad\qquad$ 1
Δm^2_{sol} $\qquad\qquad\qquad$ −1
1 $\qquad\qquad\qquad\qquad$ 1
$\qquad\qquad\qquad$ −1
$|\sin\theta_{13}|$

Δm^2_{atm}

$\sin^2\theta_{23}$
3 $\qquad\qquad\qquad\qquad$ 1
$\sin^2\theta_{13}$ $\qquad\qquad$ −1

INVERTED

Fractional Flavor Content varying $\cos\delta$

independent of
$sign(\sin\delta_{CP})$,
Majorana phases α, β

$$D \equiv \frac{1}{2} - \sin^2\theta_{23}$$
$$= (|U_{\tau 3}|^2 - |U_{\mu 3}|^2)/2(1 - |U_{e3}|^2)$$

$$|\nu_e, \ \nu_\mu, \ \nu_\tau\rangle^T_{flavor} = U_{\alpha i} |\nu_1, \ \nu_2, \ \nu_3\rangle^T_{mass}$$
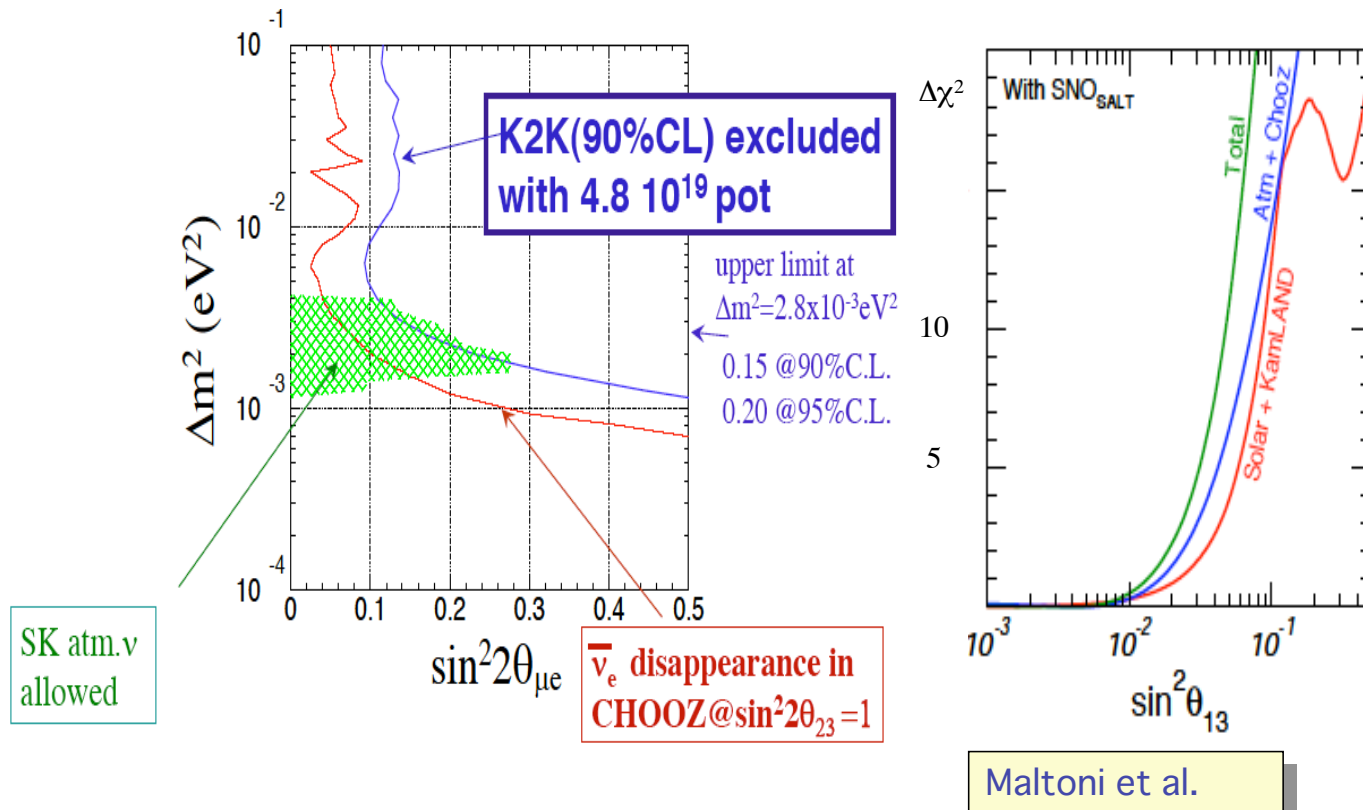
$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Atmos. L/E $\mu \to \tau$ $\quad$ Atmos. L/E $\mu \leftrightarrow e$ $\quad$ Solar L/E $e \to \mu, \tau$ $\quad$ $0\nu\beta\beta$ decay

500km/GeV $\qquad\qquad\qquad\qquad$ 15km/MeV

No indication yet of nonzero θ_{13} from atmospheric, solar and terrestrial ν

K2K(90%CL) excluded with 4.8 10^{19} pot

upper limit at
$\Delta m^2 = 2.8 \times 10^{-3} eV^2$

0.15 @90%C.L.
0.20 @95%C.L.

$\Delta m^2 \ (eV^2)$

$\sin^2 2\theta_{\mu e}$

SK atm.ν allowed

$\overline{\nu}_e$ disappearance in CHOOZ@$\sin^2 2\theta_{23} = 1$

$\Delta\chi^2$ With SNO$_{SALT}$

Total

Atm + Chooz

Solar + KamLAND

$\sin^2 \theta_{13}$

Maltoni et al.

Chooz bound $\sin^2 \theta_{13} < 0.04$

Quest for ν_e fraction in ν_3: $\sin^2\theta_{13}$

- Current LBL (MINOS)

- Atmospheric Neutrinos

- Low and High Energy Solar Neutrinos

- Supernova Neutrinos

- Short Baseline Reactor (Double Chooz, ...)

- Future Long Baseline (T2K, NuMI, BNL2?, ...)

- Neutrino Factories
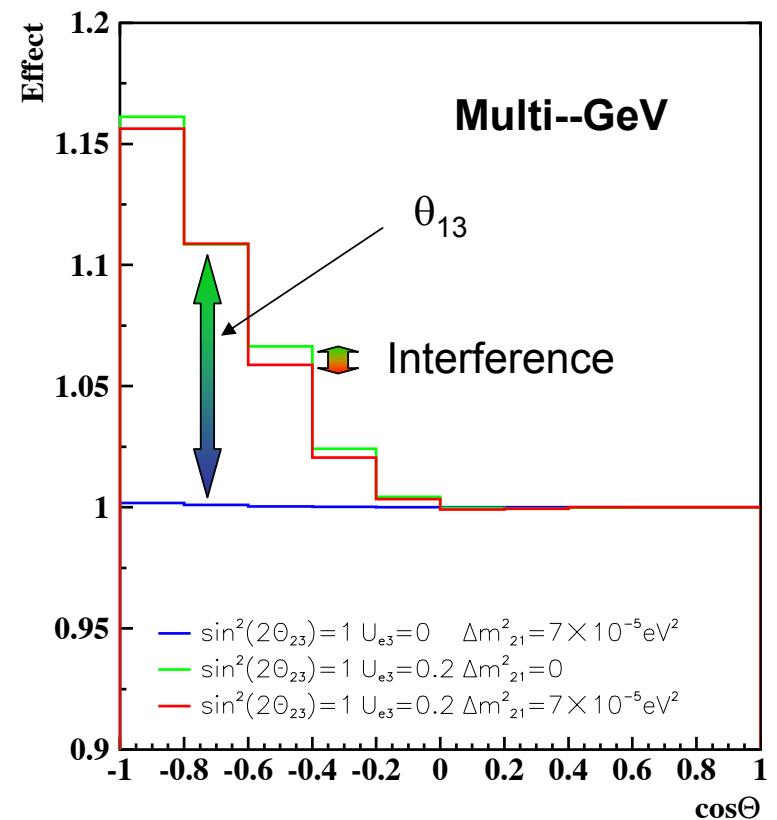
- Beta Beams

MINOS:
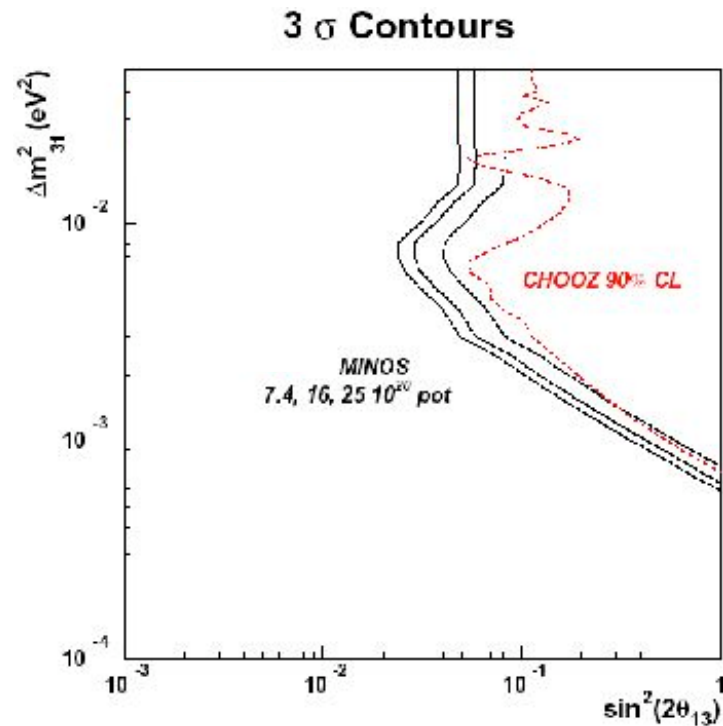
Has some sensitivity to ν_e above backgrounds.
Primary goal is to measure $|\delta m_{32}^2|$ to 10%

Atmospheric Neutrinos

SK - Suzuki

— $|U_{e3}|=0.2$

— $\Delta m_{12}^2 = 7 \times 10^{-5} eV^2$

— **Interference**

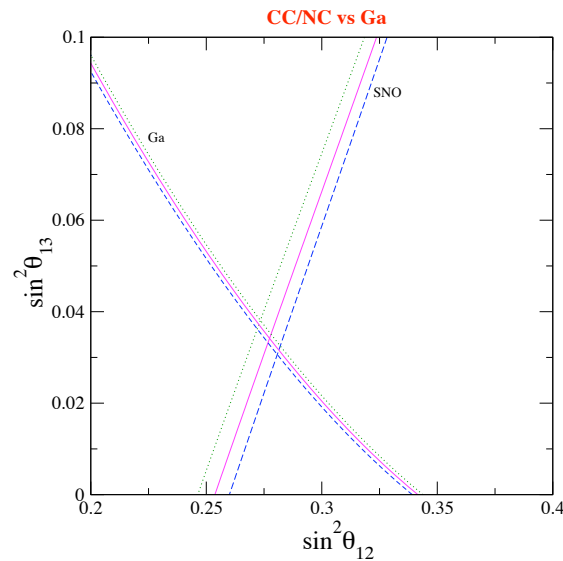- ## Low and High Energy Solar Neutrinos

Goswami + Smirnov
hep-ph/0411359

CC/NC vs Ga

Figure 6: The iso-contours of CC/NC = 0.31 at SNO and Q_{Ge} = 68.1 SNU in Ga experiments in the $\sin^2\theta_{12} - \sin^2\theta_{13}$ plane for different values of Δm_{21}^2 : $\Delta m_{21}^2 = 9 \cdot 10^{-5}$ eV^2 - the dotted lines; $\Delta m_{21}^2 = 8 \cdot 10^{-5}$ eV^2 - the solid lines; $\Delta m_{21}^2 = 7 \cdot 10^{-5}$ eV^2 - the dashed lines.

$$\frac{CC}{NC} \sim \cos^2\theta_{13}\sin^2\theta_{12} + \cdots$$

$$\sin^2\theta_{13} \uparrow \quad \Rightarrow \quad \sin^2\theta_{12} \uparrow$$

$$Ga \sim \cos^4\theta_{13}\cos^4\theta_{12} + \cdots$$

$$\sin^2\theta_{13} \uparrow \quad \Rightarrow \quad \sin^2\theta_{12} \downarrow$$

$$\sin^2\theta_\odot^{8B} \approx \sin^2\theta_{12} - 0.9\sin^2\theta_{13}$$
$$\sin^2\theta_\odot^{8pp} \approx \sin^2\theta_{12} + 1.5\sin^2\theta_{13}$$

$$\sin^2\theta_\odot^{8pp} - \sin^2\theta_\odot^{8B} \approx 2.4\sin^2\theta_{13}$$

Nunokawa, Zukanovich + SP
hep-ph/0511nnn

$$\sin^2\theta_\odot^{8pep} \approx \sin^2\theta_{12} + (0.5???)\sin^2\theta_{13}$$

Short Baseline $\bar{\nu}_e$ Disappearance: aka Reactor:

$$1 - P_{\nu_e \to \nu_e} = \sin^2 2\theta_{13} \left[\sin^2 \Delta_{atm} + \mathcal{O}\left(\frac{\Delta_{solar}}{\Delta_{atm}}\right) \right] + \mathcal{O}\left(\frac{\Delta_{solar}}{\Delta_{atm}}\right)^2$$

$\qquad\qquad\qquad$ >1% $\qquad\qquad$ 1 $\qquad\qquad\qquad$ <3% $\qquad\qquad\qquad$ <0.1%

kinematical phase $\qquad \Delta_{atm} = \dfrac{\delta m_{atm}^2 L}{4E} = 1.27 \dfrac{\delta m_{atm}^2 L}{E}$

The $\mathcal{O}\left(\frac{\Delta_{solar}}{\Delta_{atm}}\right)$ VANISHES if

$$\begin{aligned}
\delta m_{atm}^2 &= \cos^2\theta_{12}\, \delta m_{31}^2 + \sin^2\theta_{12}\, \delta m_{32}^2 \\
&= m_3^2 - \underline{(\cos^2\theta_{12}\, m_1^2 + \sin^2\theta_{12}\, m_2^2)} \Rightarrow \delta m_{31}^2 \quad when\ \theta_{12} \Rightarrow 0
\end{aligned}$$

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ Average ν_e mass in 1 and 2.

This is the $|\delta m_{atm}^2|_e$ that could be measured in such an experiment.

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ Nunokawa, Zukanovich + SP
$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ hep-ph/0503283

- Normal Hierarchy: $|\delta m_{atm}^2|_e > |\delta m_{atm}^2|_\mu$
- Inverted Hierarchy: $|\delta m_{atm}^2|_e < |\delta m_{atm}^2|_\mu$
- Unfortunately difference is small 1 - 2 % !!!

where $|\delta m_{atm}^2|_\mu$ from ν_μ disappearance.

$\qquad\qquad\qquad\qquad\qquad$ $|\delta m_{atm}^2|_\mu \Rightarrow \delta m_{32}^2$
$\qquad\qquad\qquad\qquad\qquad$ when $\theta_{12} \Rightarrow 0$

Double Chooz Sensitivity
(5 year run)

$\sin^2(2\theta_{13})$ @ 90% CL

Double Chooz
Goal

$\Delta m^2 = 0.002$

$\Delta m^2 = 0.0024$

$\Delta m^2 = 0.003$

Systematic Error (%)

Original Chooz
Detector Error

David Reyna - ANL

Δm^2 (eV^2)

CHOOZ 90% CL
Excluded

90% CL

3σ

$\sin^2 2\theta_{13}$

7 GW, 50 tons, 3 years, and 1400 meters
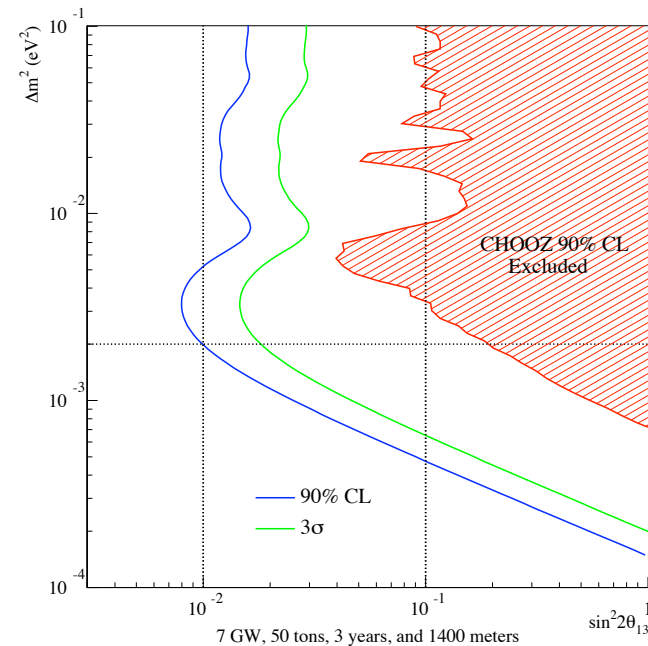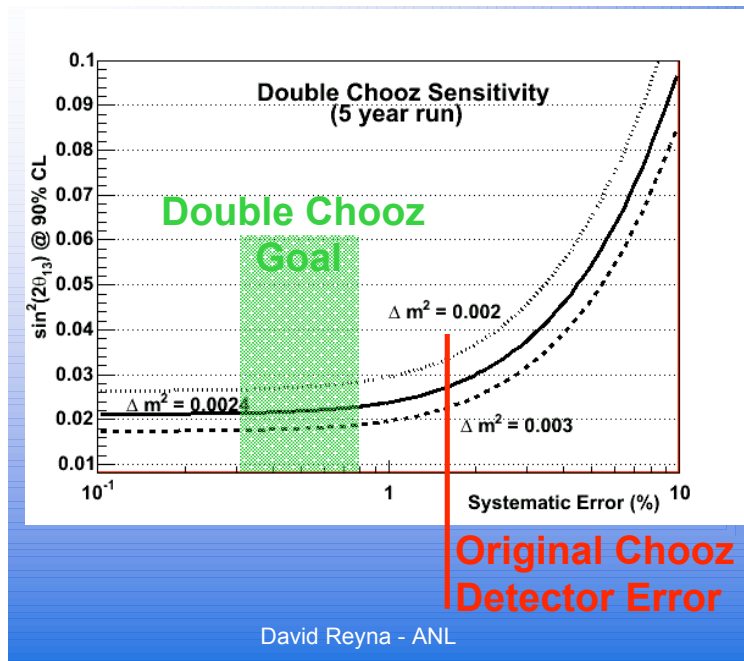
J. Link, Columbia

- Pure measurement of $\sin^2 \theta_{13}$
  — no contamination from
  $\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$ degeneracy.

With Off-axis measurements of $\nu_\mu \to \nu_e$:

- of $\sin^2 \theta_{23} \sin^2 \theta_{13}$ can help resolve
  $\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$ degeneracy for $\sin^2 2\theta_{23} \neq 1$.
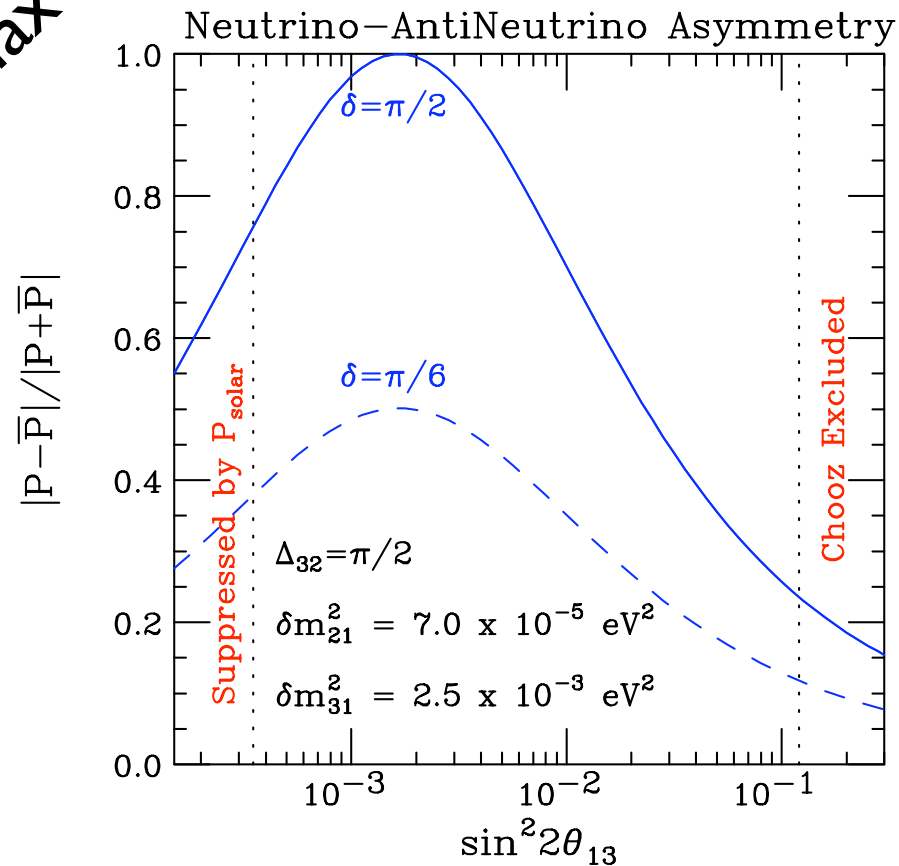
- Help resolve hierarchy and $\sin \delta \neq 0$, maybe.

VAC LBL: $\nu_\mu \to \nu_e$

CP violation !!!

$$P_{\mu \to e} \approx \mid \sqrt{P_{atm}}\, e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \mid^2$$

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\ \sin\Delta_{31}$ and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\ \sin\Delta_{21}$

1st Vac Osc Max

Neutrino−AntiNeutrino Asymmetry

$\delta = \pi/2$

$\delta = \pi/6$

Suppressed by P_{solar}

Chooz Excluded

$\Delta_{32} = \pi/2$

$\delta m_{21}^2 = 7.0 \times 10^{-5}\ eV^2$

$\delta m_{31}^2 = 2.5 \times 10^{-3}\ eV^2$

$|P - \overline{P}| / |P + \overline{P}|$

$\sin^2 2\theta_{13}$

$\nu_\mu \longrightarrow \nu_e$ with MATTER

CP violation !!!

$$P_{\mu \to e} \approx | \sqrt{P_{atm}}\, e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} |^2$$

where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \dfrac{\sin(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)} \Delta_{31}$

$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1}$,

$\pm = sign(\delta m_{31}^2)$

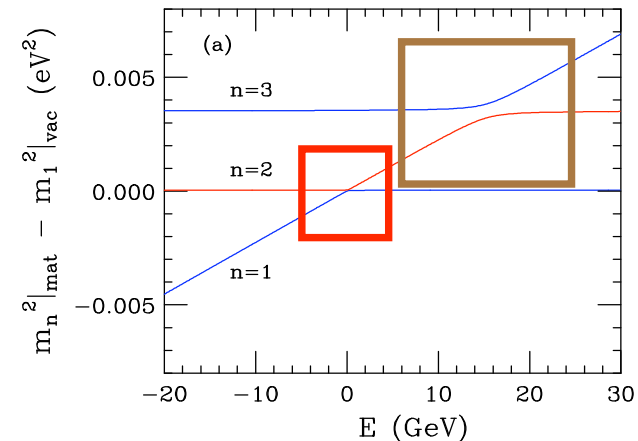and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \dfrac{\sin(aL)}{(aL)} \Delta_{21}$

$\Delta_{ij} = |\delta m_{ij}^2| L/4E$

$\boxed{\{\delta m^2 \sin 2\theta\} \text{ is invariant}}$

$\sin\Delta_{31} \Rightarrow \left(\dfrac{\Delta_{31}}{\Delta_{31} \mp aL}\right) \sin(\Delta_{31} \mp aL)$

$\sin\Delta_{21} \Rightarrow \left(\dfrac{\Delta_{21}}{\Delta_{21} \mp aL}\right) \sin(\Delta_{21} \mp aL)$

$\sin\Delta_{32} \Rightarrow \sin\Delta_{32}$

Matter effects are IMPORTANT when $\sin(\Delta \mp aL) \neq (\Delta \mp aL)$.

Numerous Approaches to Studying $\nu_\mu \leftrightarrow \nu_e$ Transitions:

- Off Axis - Narrow Band Beams $\nu_\mu \rightarrow \nu_e$ (T2K and NOvA)

- On Axis - Broadband Beam $\nu_\mu \rightarrow \nu_e$ (BNL 2 HSK)

- Neutrino Factory $\nu_e \rightarrow \nu_\mu$

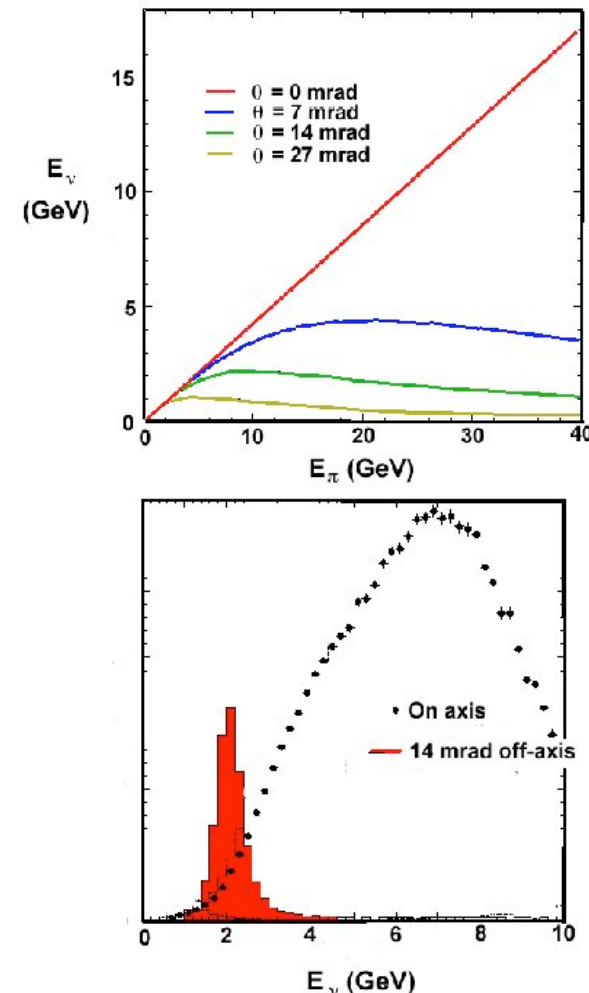- Beta Beams $\nu_e \rightarrow \nu_\mu$

Off-Axis Neutrino Beams:

$$E_\nu = \frac{0.43 E_\pi}{(1+\theta^2\gamma_\pi^2)}$$

Off-Axis the beams are Narrow!
approx. gaussian with spread
20% $< E_\nu >$

GREAT !!!

as the primary bckgrd to ν_e
detection is π^0 coming from
higher energy NC events. (ν_e
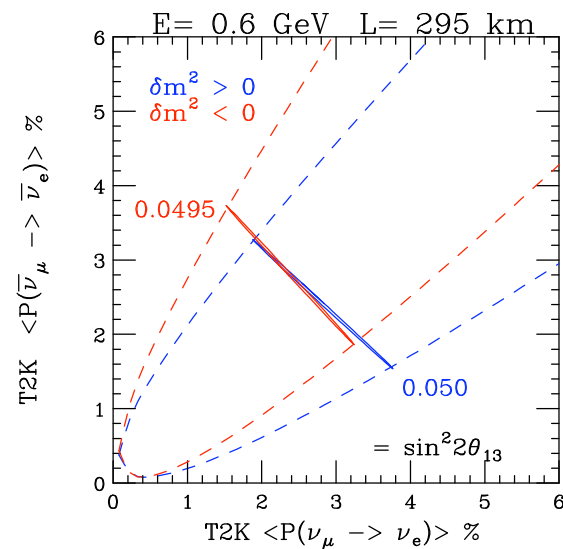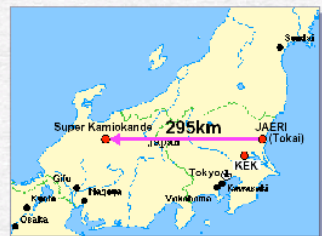contamination in beam is small
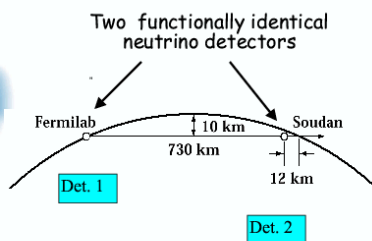0.5% and apprx known.)

BNL-proposal '94

T2K

JHF → Super-Kamiokande

- 295 km baseline
- Super-Kamiokande:
  - 22.5 kton fiducial
  - Excellent e/μ ID
  - Additional π⁰/e ID
- Hyper-Kamiokande
  - 20× fiducial mass of SuperK
- Matter effects small
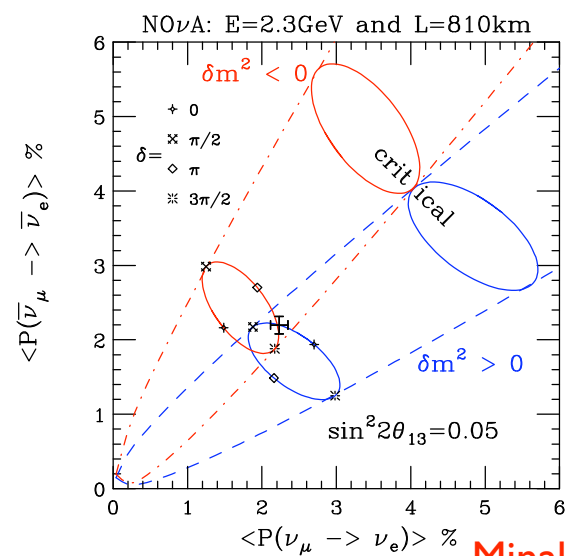- Study using fully simulated and reconstructed data

Super Kamiokande   295km   JAERI (Tokai)
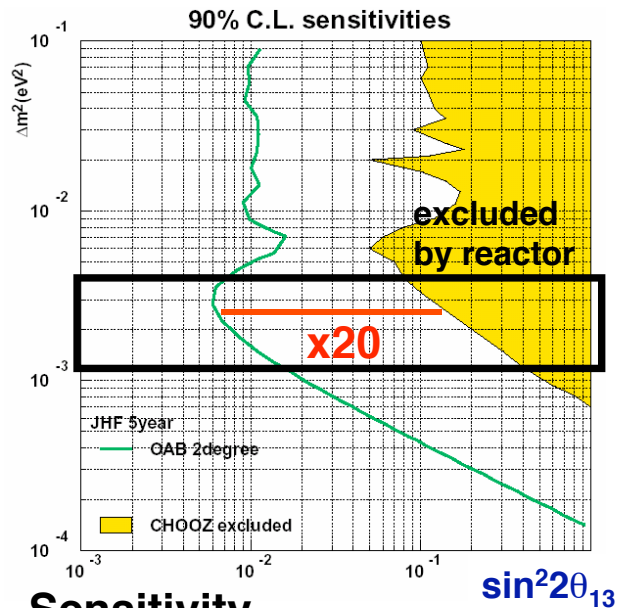
The NUMI Beamline   NOvA

Two functionally identical neutrino detectors

Fermilab   10 km   Soudan
730 km
Det. 1   12 km
Det. 2

FLARE

$E = 0.6$ GeV $L = 295$ km

$\delta m^2 > 0$
$\delta m^2 < 0$

0.0495

0.050

$= \sin^2 2\theta_{13}$

T2K $\langle P(\bar{\nu}_\mu \to \bar{\nu}_e)\rangle$ %

T2K $\langle P(\nu_\mu \to \nu_e)\rangle$ %

NOνA: $E = 2.3$ GeV and $L = 810$ km

$\delta m^2 < 0$

$\delta = $ + 0
       × π/2
       ◇ π
       ✳ 3π/2

critical

$\delta m^2 > 0$

$\sin^2 2\theta_{13} = 0.05$

$\langle P(\bar{\nu}_\mu \to \bar{\nu}_e)\rangle$ %

$\langle P(\nu_\mu \to \nu_e)\rangle$ %

Minakata+Nunokawa
hep-ph/0108085

Sensitivity to θ_{13}

T2K:

Search for ν_e appearance

90% C.L. sensitivities

$\Delta m^2 (eV^2)$

excluded by reactor

x20

JHF 5year
OAB 2degree

CHOOZ excluded
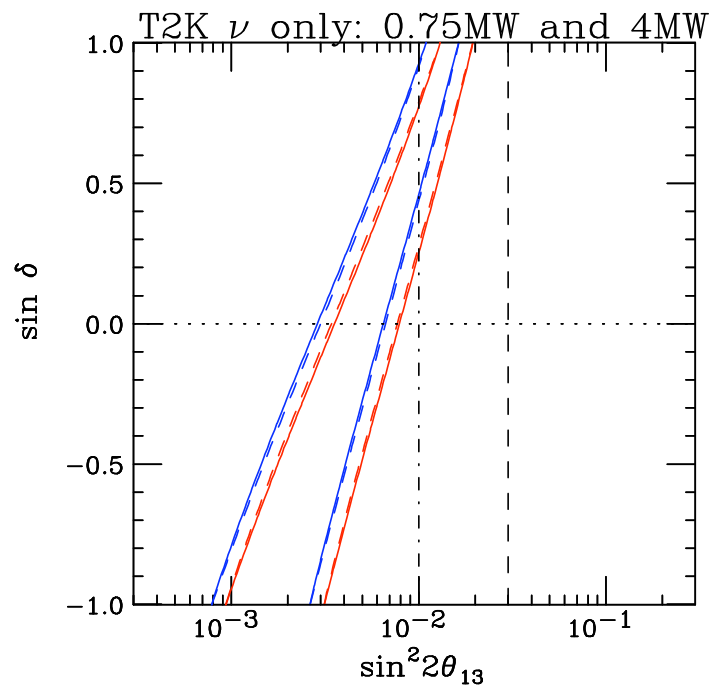
$\sin^2 2\theta_{13}$

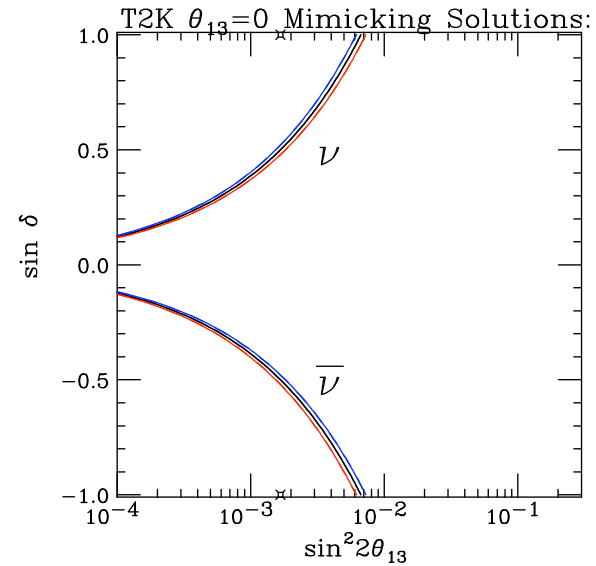**Sensitivity**

$\sin^2 2\theta_{13} > 0.006$ (90%)

5 yrs 0.75MW with SK

assumes $\delta = 0$

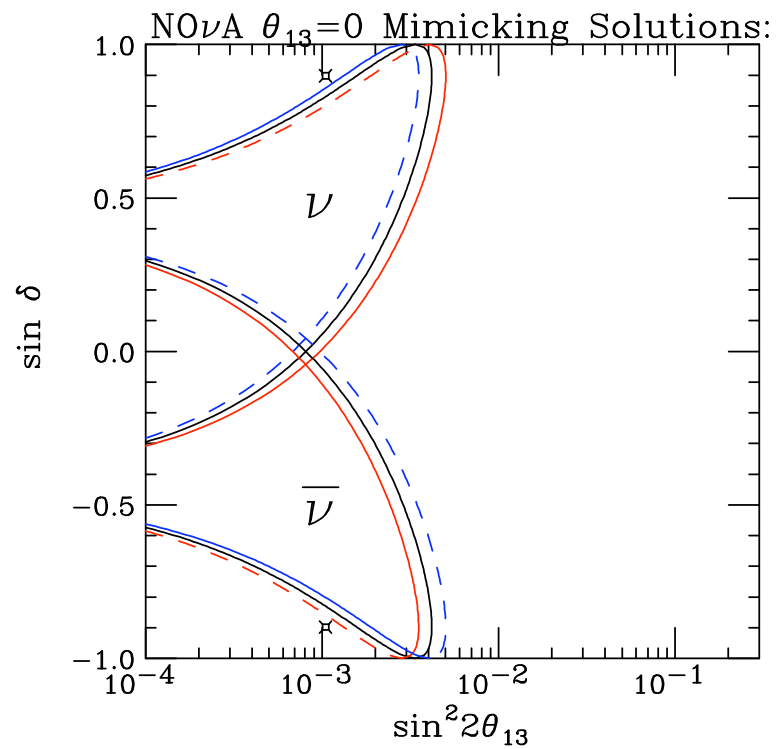**Question:** What exposure is required to reach this sensitivity if $\delta = \pm \frac{\pi}{2}$?

T2K ν only: 0.75MW and 4MW

(y-axis: $\sin \delta$, x-axis: $\sin^2 2\theta_{13}$)

Zero Mimicking Soln:

$$\sqrt{P_{atm}} = \pm 2\sqrt{P_{sol}} \sin \delta$$

T2K $\theta_{13}=0$ Mimicking Solutions:

(y-axis: $\sin \delta$, x-axis: $\sin^2 2\theta_{13}$)

ν

$\overline{\nu}$

NuMI: NOvA, FLARE

Zero Mimicking Soln:

NOνA $\theta_{13}=0$ Mimicking Solutions:

$$\sqrt{P_{atm}} = -2\sqrt{P_{sol}}\cos(\Delta_{32} \pm \delta)$$

NOνA, FLARE:

NOνA: E=2.3GeV and L=810km

$\delta m^2 < 0$

$\delta = $ + 0
     ✳ $\pi/2$
     ◇ π
     ✳ $3\pi/2$

critical

$\delta m^2 > 0$

$\sin^2 2\theta_{13} = 0.05$

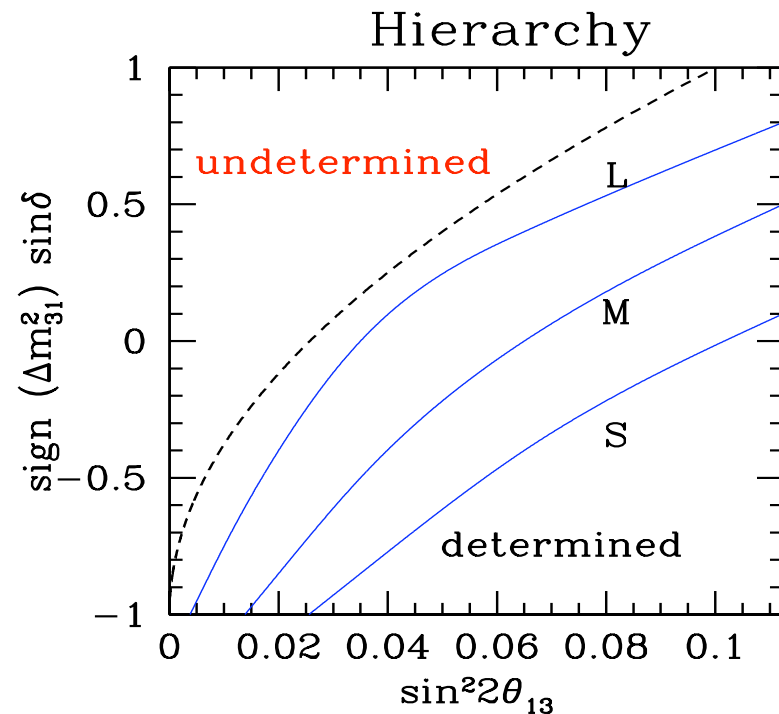$\langle P(\bar{\nu}_\mu \to \bar{\nu}_e) \rangle$ %
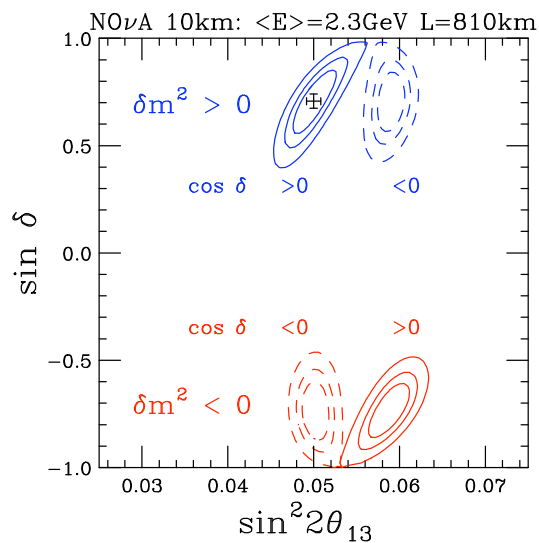
$\langle P(\nu_\mu \to \nu_e) \rangle$ %
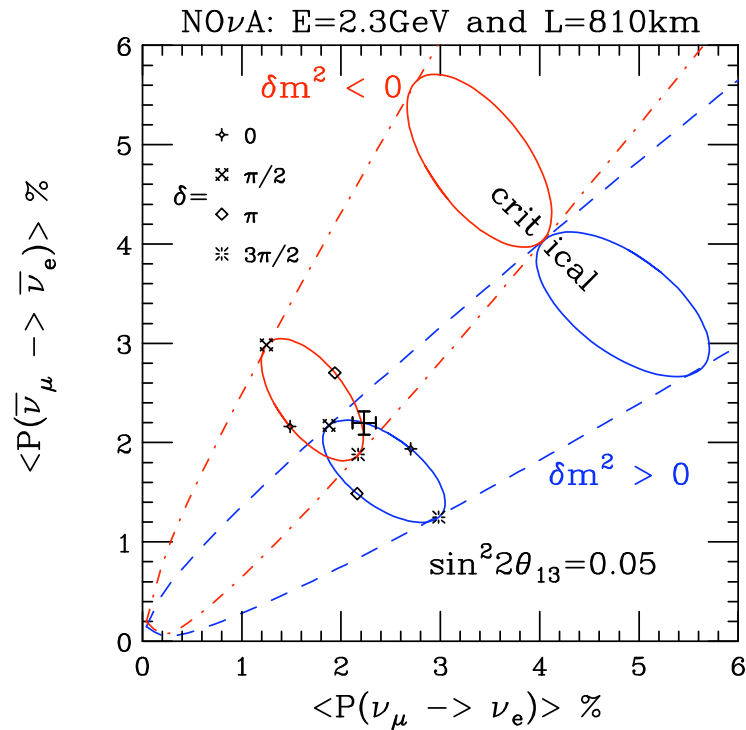
"S": 3e22 proton Ktons
=(3.5+3.5) yrs @ 6.5e20 pot/yr
x {30 ktons x 24%} or {9 ktons x 80%}

M: 5 x "S"   L: 25 x "S"

Mass x POT x Eff

Hierarchy

undetermined

L

M

S

determined

$\text{sign} (\Delta m^2_{31}) \sin\delta$

$\sin^2 2\theta_{13}$

Mena+Parke
hep-ph/0505202

NOνA 10km: <E>=2.3GeV L=810km

$\delta m^2 > 0$

$\cos \delta$ >0   <0

$\cos \delta$ <0   >0

$\delta m^2 < 0$

$\sin \delta$

$\sin^2 2\theta_{13}$

Vac Osc Max

T2K 3°: <E>=0.6GeV L=295km
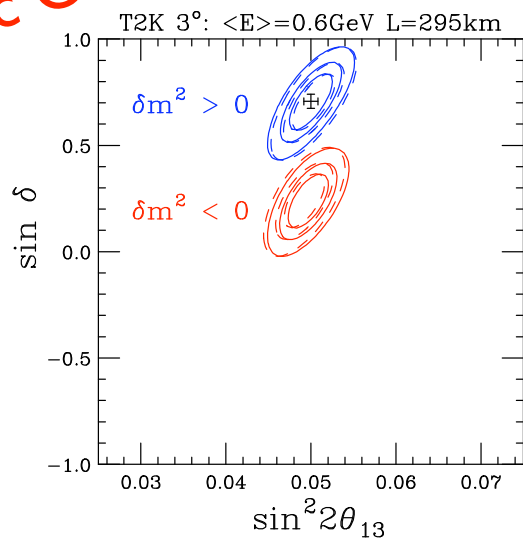
$\delta m^2 > 0$

$\delta m^2 < 0$

$\sin \delta$

$\sin^2 2\theta_{13}$

$$\langle \sin \delta \rangle_+ - \langle \sin \delta \rangle_- = 1.41 \sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

$$\left| \langle \sin \delta \rangle_{true}^{T2K} - \langle \sin \delta \rangle_{true}^{NO\nu A} \right| \approx 0.$$

factor of 3 !!!

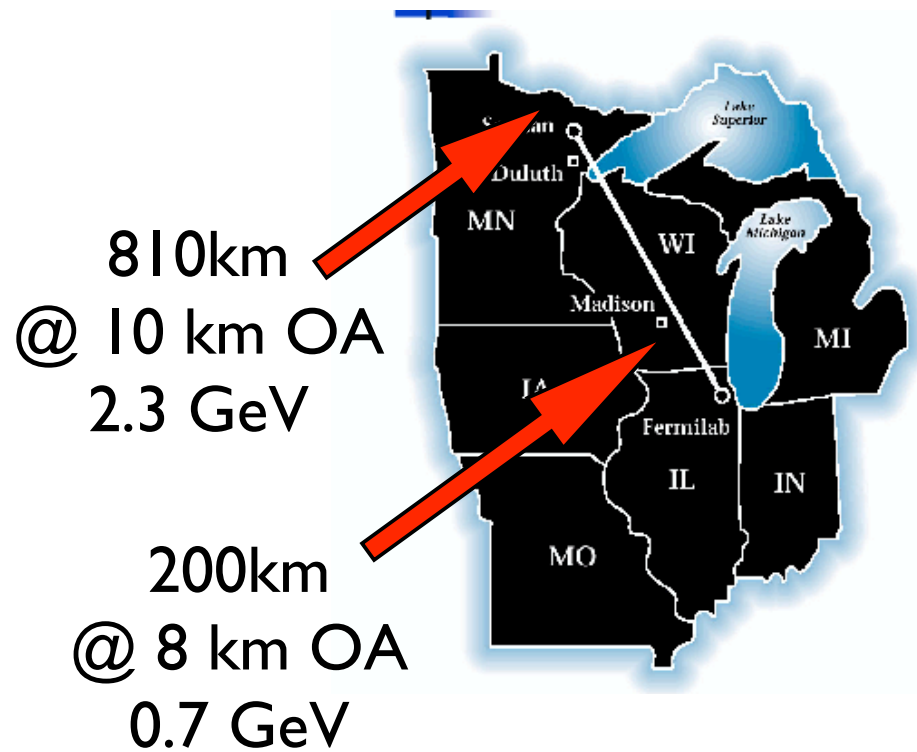$$\left| \langle \sin \delta \rangle_{fake}^{T2K} - \langle \sin \delta \rangle_{fake}^{NO\nu A} \right| = 0.94 \sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}.$$

$$\langle \sin \delta \rangle_+ - \langle \sin \delta \rangle_- = 0.47 \sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

Mena + SP
hep-ph/0408070

NOvA plus "NEAR" DETECTOR

Mena, Palomares, Pascoli
hep-ph/0504015

810km
@ 10 km OA
2.3 GeV

200km
@ 8 km OA
0.7 GeV

approx same
E/L

Neutrino - Neutrino

ν @810km + ν @200km

$\delta m_{31}^2 < 0$

$\delta m_{31}^2 > 0$

N_{200} /10kt/6.5e20 pot

N_{810} /10kt/6.5e20 pot
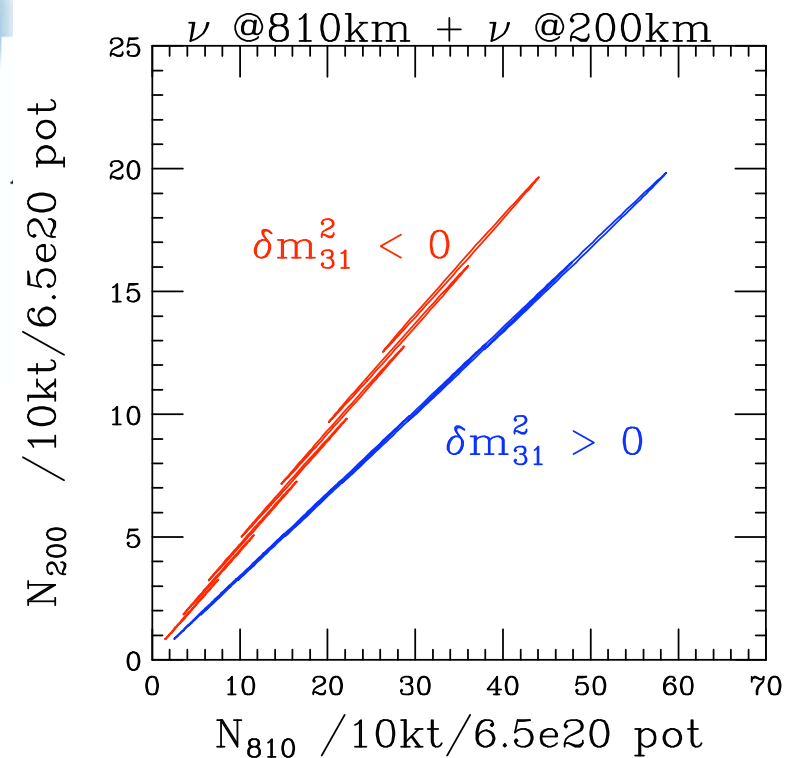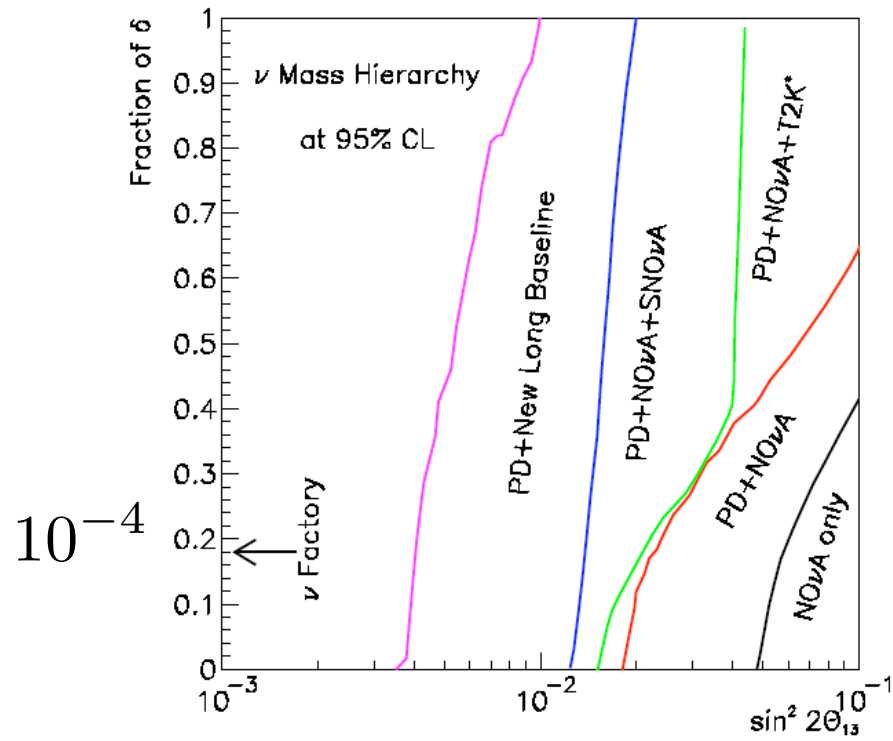
$\sin^2 2\theta_{13} = (1, 2, 3, 4.3, 6, 7.4, 9.5)\ 10^{-2}$

Mass Hierarchy from Off Axis

10^{-4}

Fermilab Proton Driver Report

Leptonic CP and T Violation in Neutrino Oscillations

$$\nu_\mu \leftrightarrow \nu_e \qquad \overset{\text{CP}}{\Longleftrightarrow} \qquad \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e \qquad \text{Super-Beams}$$

$$\text{T} \quad \Updownarrow \qquad \qquad \qquad \Updownarrow \quad \text{T}$$

$$\nu_e \leftrightarrow \nu_\mu \qquad \overset{\text{CP}}{\Longleftrightarrow} \qquad \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu \qquad \text{Nu-Factory}$$
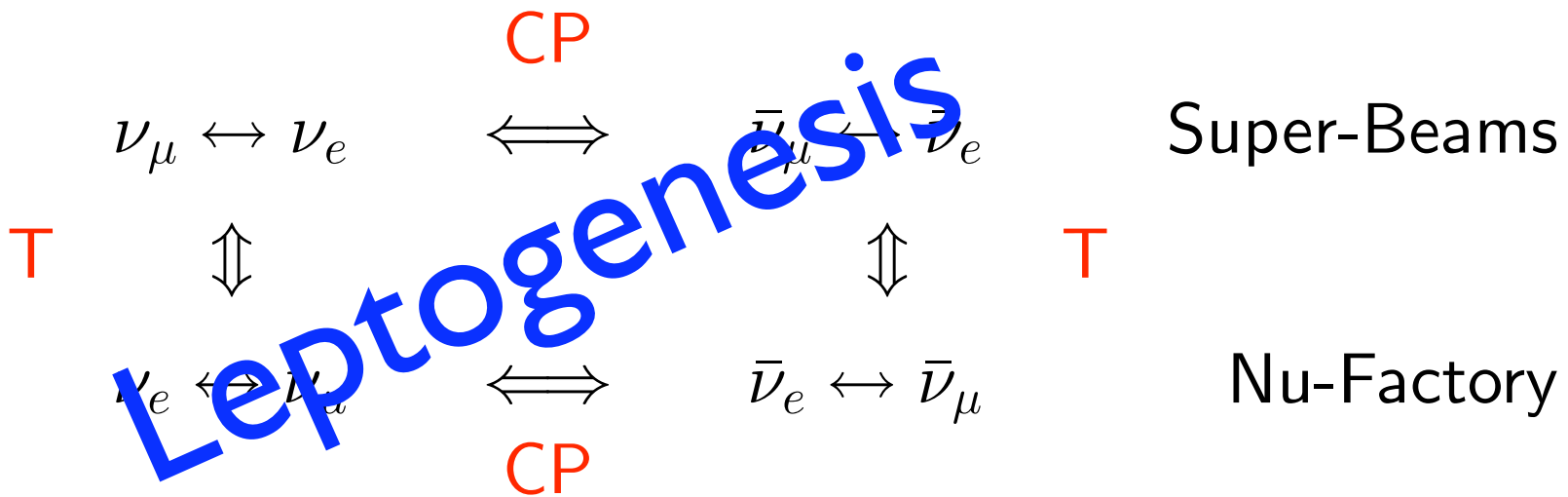
Leptogenesis

CP Violation and Leptogenesis

- For most Neutrino Mass Models there is a relationship between the Dirac CP phase δ and Majorana CP phases $\alpha_2, \ \alpha_3$.

- At a minimum they are all zero or all non-zero.

- $\alpha_2, \ \alpha_3$ are responsible for Leptogenesis in the early universe by allowing for different decay rates of Neutral Heavy Leptons:
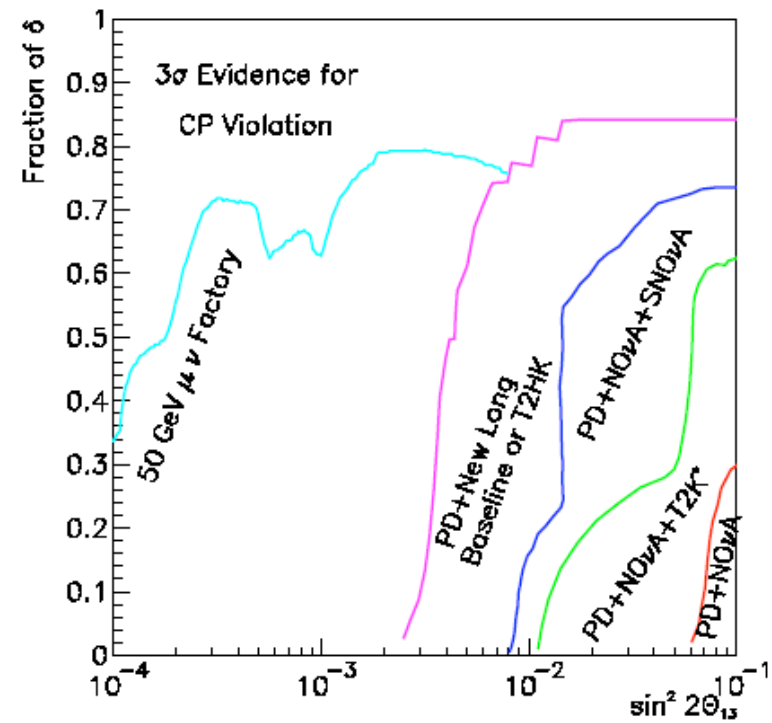
$$N \to l^+ \phi^- \text{ and } N \to l^- \phi^+$$

- $B = \frac{1}{2}(B - L) + \frac{1}{2}(B + L)$, however $(B + L)$ violated.

- Hence the Dirac CP violating phase, δ, is a handle on Leptogenesis and hence Baryogenesis.

CP Violation:
NOvA, FLARE
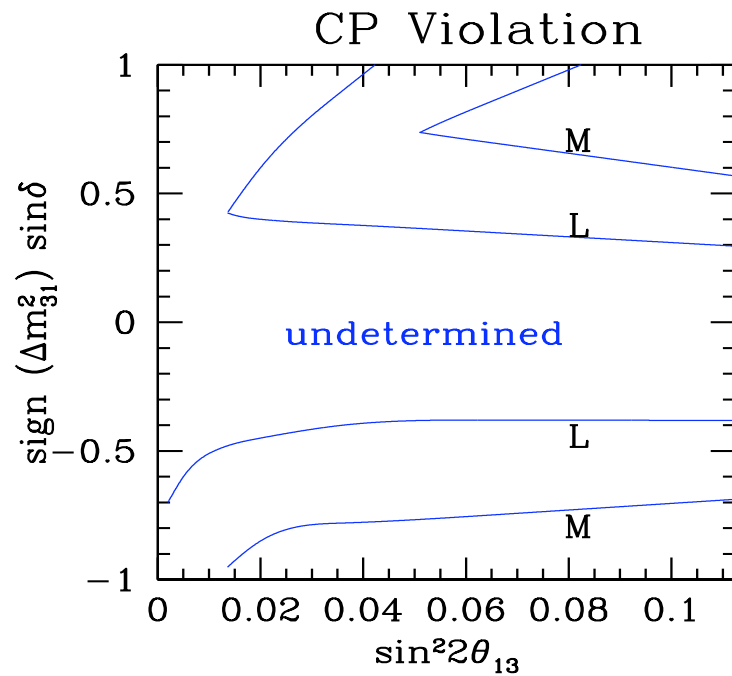
CP Violation

CP Violation

Solving Degeneracies:

Reactor + Off Axis:

Variable Measured	LBL $\nu_\mu \to \nu_\mu$	LBL $\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$	Reactor $\bar{\nu}_e \to \bar{\nu}_e$	Comments
$|\Delta m_{32}^2|$	Y	n	n	magnitude but not sign
$\sin^2 2\theta_{23}$	Y	n	n	$\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$ ambiguous
$\sin^2 \theta_{13}$	n	n	Y	direct measurement
$\sin^2 \theta_{23} \sin^2 \theta_{13}$	n	Y	n	combination of θ_{23} and θ_{13}
$\text{sign}(\Delta m_{32}^2)$	n	Y	n	via matter effects
$\cos \theta_{23} \sin \delta_{CP}$	n	Y	n	CP violation
$\cos \theta_{23} \cos \delta_{CP}$	n	?	n	extremely difficult

On Axis Beams:

- 28 GeV protons. I MW beam power. Horn focussed

- 500 kT water Cherenkov detector.

- baseline > 2500 km. WIPP, Henderson, Homestake
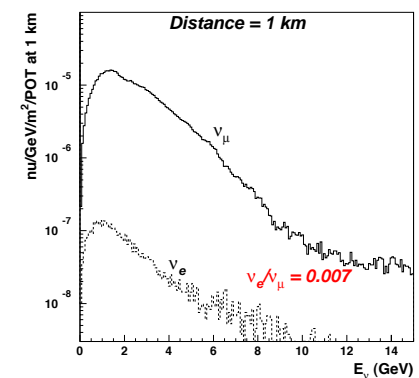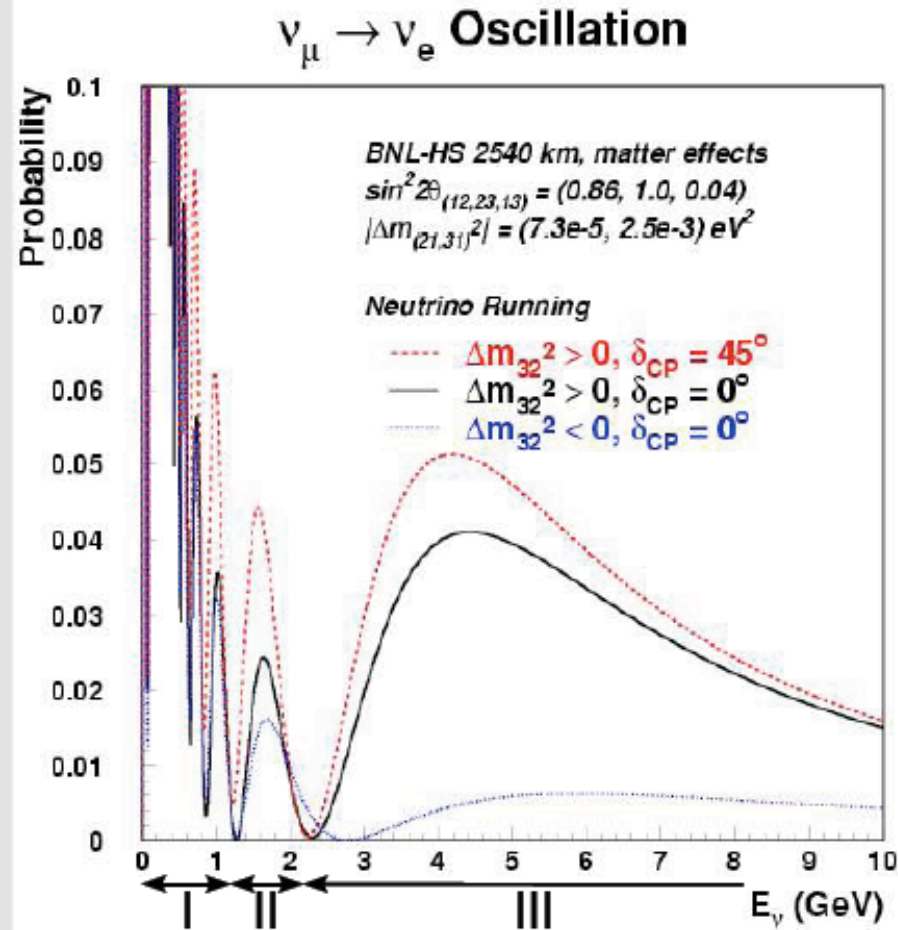
Why Broadband Beam?

observe multiple nodes
extraction of oscillating
signal from background.

larger energies
  larger cross sections
  less running time for
  anti-neutrinos
Sensitive to different
parameters in different
energy regions:

	I	II	III
$\sin^2 2\theta_{13}$	+	+	+
$\text{sign}(\Delta m^2_{32})$	0	0	++
δ_{CP}	+	++	+
solar	++	+	+

$\nu_\mu \rightarrow \nu_e$ **Oscillation**

BNL-HS 2540 km, matter effects
$\sin^2 2\theta_{(12,23,13)} = (0.86, 1.0, 0.04)$
$|\Delta m_{(21,31)}^2| = (7.3\text{e-}5, 2.5\text{e-}3)\,eV^2$

Neutrino Running

- - - - $\Delta m_{32}^2 > 0,\ \delta_{CP} = 45°$
——— $\Delta m_{32}^2 > 0,\ \delta_{CP} = 0°$
········· $\Delta m_{32}^2 < 0,\ \delta_{CP} = 0°$

E_ν (GeV)

• Many Off Axis experiments in one!

Why is $\nu_e \to \nu_\mu$ at a ν Factory Easy?

- Neutrinos/MW proton power *cf* conventional beams $\propto (E_\mu/15)^3$

- No Intrinsic ν_μ in the beam, only $\bar{\nu}_\mu$'s

- Charge of Muon easier to measure than e/π^0 separation

- Detector Technology straightforward (see MINOS)

- Backgrounds at $\leq 10^{-4}$ level, not few $\times 10^{-3}$

Comparison of Fluxes
per MegaWatt
at each experiment:

- Higher E means larger cross section, more events.

- Higher E allows larger L for same E/L, bigger matter effects (amplifies P_{atm}).
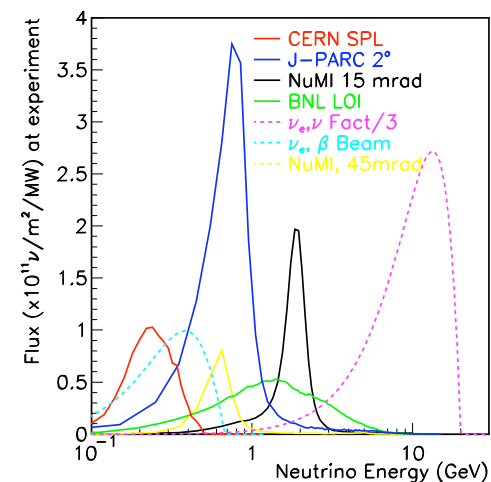
Note ν Factory flux
divided by 3
to fit on graph!

Conclusions:

the θ_{13} window

is a

WONDERFUL OPPORTUNITY:

- $\sin^2 \theta_{13} \neq 0$ Reactor and LBL needed.

- For Mass Hierarchy we need more than one Off-Axis Exp. T2K + "NuMI exp." OR an On-Axis Exp.

- CP violation: Need many events: this implies Big detectors, Powerful Source, High Eff. (also $$$)
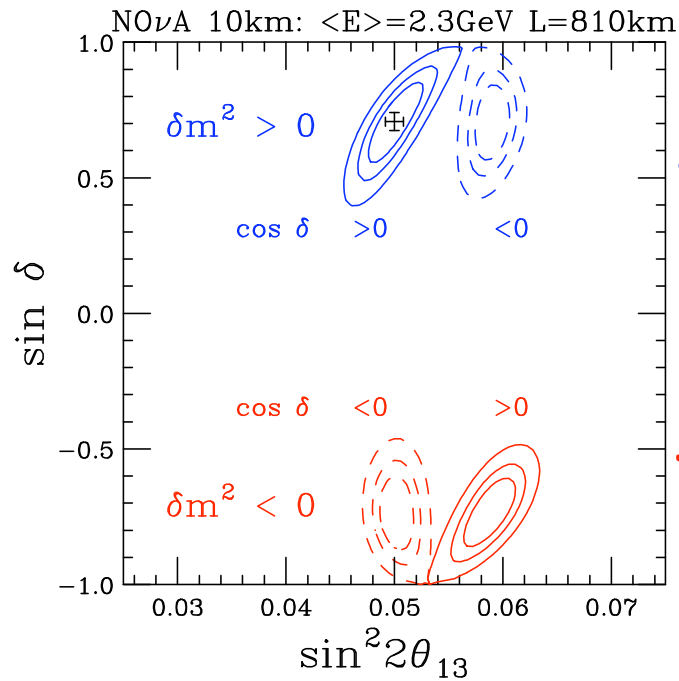
new technology needed

Star Trek: The Next Generation

Geordi La Forge: in "The Enemy"

The visor "sees" Neutrinos!!!

... but this requires special New Physics !!!

Parameter Degeneracies:

NOνA 10km: <E>=2.3GeV L=810km

$\delta m^2 > 0$

$\cos \delta$ >0   <0

$\cos \delta$ <0   >0

$\delta m^2 < 0$

sin δ

$\sin^2 2\theta_{13}$

<E>=2.3GeV   L=810km

NOνA   <P($\bar{\nu}_\mu \to \bar{\nu}_e$)> %
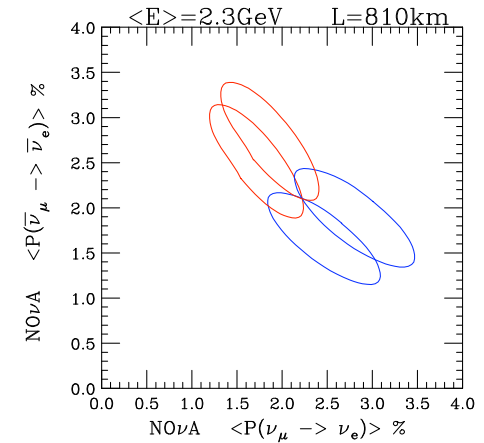
NOνA   <P($\nu_\mu \to \nu_e$)> %

$\langle \sin \delta \rangle_+ - \langle \sin \delta \rangle_-$

$$= \left(\frac{4}{3\pi}\right)^2 \left(\frac{\tan \theta_{23}}{\sin 2\theta_{12}}\right) \left(\frac{\delta m_{31}^2}{\delta m_{21}^2}\right) (a_E L) \sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

$$(a_E L)_{NOvA} = 3 \, (a_E L)_{T2K}$$

$$a \approx \frac{1}{4000 \ km}$$

Burget-Castell etal
hep-ph/0103258

$\Longleftrightarrow$

$$\sim \Delta_{31} \cot \Delta_{31}$$

0 when $\Delta_{31} = \pi/2$

Mena + SP
hep-ph/0408070

T2K:

$$\sqrt{P_{atm}} = \pm 2\sqrt{P_{sol}}\sin\delta$$

T2K will operate at Vacuum Oscillation Maximum

$$P(\mu \to e) = P_{atm} - 2\sqrt{P_{atm}P_{sol}}\sin\delta + P_{sol}$$

at $\sin^2 2\theta_{13} = 0.006$ $\qquad P_{atm} = 4P_{sol}$

($P_{sol} = 0.1\%$)

Therefore

$$P(\delta = 0) = 5P_{sol}$$

$$P(\delta = -\tfrac{\pi}{2}) = 9P_{sol} \quad \text{half exposure required.}$$

$$P(\delta = \tfrac{\pi}{2}) = P_{sol} \quad \text{NO contribution from } \theta_{13} \text{ !!!!}$$

Also

$$P(\delta = -\tfrac{\pi}{2}) = 5P_{sol} \quad \text{when } \sin^2 2\theta_{13} = 0.003$$

$$P(\delta = \tfrac{\pi}{2}) = 5P_{sol} \quad \text{when } \sin^2 2\theta_{13} = 0.02$$

T2K $\theta_{13}{=}0$ Mimicking Solutions:

ν

$\overline{\nu}$

sin δ / $\sin^2 2\theta_{13}$

T2K ν only: 0.75MW and 4MW

sin δ / $\sin^2 2\theta_{13}$